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PRODUCTION AND TRANSFER OF UV PHOTONS IN NON-HOMOGENEOUS SPHERICAL CLOUDS

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1. Introduction

Due to screening by dust particles, the UV radiation field of intersteellar origin is practically inexistent within very dense interstellar clouds. However, as argued first by Prasad and Tarafdar (1983), it appears possible that the cosmic-ray excitation of the Lyman and Werner systems of the hydrogen molecule could originate a chemically-significant flux of UV photons even within such dense clouds.

This suggestion by Prasad and Tarafdar was investigated later by Lepp et al (1986), Sternberg et al (1987), Gredel et al (1987), who found that cosmic-ray induced photon production may significantly affect the chemistry of dense clouds.

In view of the important implications that the existence of such photons may have for the gas and dust evolution, and taking into account that the transfer of radiation inside a cloud is strongly affected by extinction and scattering properties of dust particles, as well as by their distribution, it seemed worthwhile to re-analyze the c.r.- induced production of UV photons, giving particular emphasis to the treatment of the transfer of the emitted photons.

Elsewhere (Aiello et al, 1987) we computed the c.r. - induced UV flux in a homogeneous spherical cloud as a function of the extinction and scattering properties of dust. In the present work we extended the analysis to the case of clouds with radial gas and dust density gradients.

2. UV Photons production and transfer

The equation of statistical equilibrium for the vibrational levels of the upper electronic states ($B^1\Sigma u^+$, $C^1\Pi u$) is:

$$n_u[\sum_{1}^{14} {}_j(A_{uj} + B_{uj} \langle I_{uj}\rangle] = n_o(C_{ou} + B_{ou} \langle I_{ou}\rangle) + \sum_{1}^{14} {}_j n_j B_{ju} \langle I_{uj}\rangle \quad [1]$$

where n_u, n_o, n_j are, respectively, the populations of the upper electronic vibrational level, of the ground electronic level with $v''= 0$ and of the jth vibrational level of the electronic ground.

Because of the low level of expected UV fluxes we can disregard the stimulated emission with respect to the spontaneous emission. We can also overlook the absorption from electronic ground states with $v''>0$.

Finally, since the photons emitted in the ($u \rightarrow v''=0$) transitions are absorbed very close to the point at which they are generated ("on the spot"), we can put the corresponding fields as equal to the source functions.

So, the equation [1] becomes:

$$n_u = n_o C_{ou}(\sum_{1}^{14} {}_j A_{uj})^{-1} \quad [2]$$

The transfer of emitted photons has been computed by using a method the outlines of which have been given by Van de Hulst and Davis (1961), adapted to a spherical symmetry with a radial gradient of dust density.

The approach is the following: let I_0 be the intensity of the zero order and let I_n, the intensity of the light which has been scattered n times in succession. We will proceed step by step from the I_n to the I_{n+1}, and will then compute the total scattered light: $\langle I\rangle = \langle I_0\rangle + \Sigma_n\langle I_n\rangle$. The intensities are averaged over the line profiles as well as over the solid angle.

The source function for the scattering of order n in each point of the cloud is related to the intensity of the order n-1. In other words the calculation scheme is:

S_0(molecular emission) $\Rightarrow I_0 \Rightarrow S_1 \Rightarrow I_1 \Rightarrow S_2 \Rightarrow I_2 \Rightarrow \ldots\ldots$

Mathematical and computational details can be found in Aiello et al (1984).

For the photon fluxes we obtain the following expression:

$$N_{uj} = C_{ou}\, R\, F(r/R,\nu_{uj};\ \tau,\gamma,g)\ A_{uj}\ n_o(1-\psi)\ (\sum_1^{14} A_{uj})^{-1} \quad [3]$$

Let us to discuss the quantities involved in [3]:

ψ is a correction factor that allows for the fraction of absorption events that lead to the dissociation of the molecules. Following Jura (1974) we put $\psi = 0.1$.

The excitation coefficients, C_{ou} were computed by making use of the results from analysis of the effects of the energy deposition by c.r. within a molecular hydrogen cloud performed by Aiello & Cecchi-Pestellini (1987). In this computation the interstellar proton spectrum by Webber & Yushak (1983), extrapolated down to 1 MeV, was adopted. A check on the validity of our choice is represented by the value of the resulting ionization rate $\zeta=3\mathrm{x}10^{-17}$ s^{-1} per H_2 molecule, wich is in good agreement with the values derived from the analysis of thermal balance within dark clouds (Duley & Williams, 1984).

The efficiency factor F is a function of the cloud structure as well as of the extinction and scattering properties of the dust.

a) Extinction properties

The wavelength dependence of the optical depth depends on the extinction law adopted. The latter has been studied in the direction of many thousands of stars located in different galactic regions and astrophysical environments. The mean extinction curve (MIEC) so derived (Savage & Mathis, 1979) can be considered as representative of the general properties of dust in the diffuse medium and in old associations (Aiello et al., 1988). However, extinction and polarization data show that in dense clouds and in regions of recent star formation, dust grains are likely to have different properties: in particular, their size distribution appears to be biased towards larger radii that results in a more or less marked flattening of the extinction curve in the far UV spectral region. Therefore, the use of MIEC in radiation transfer computations could be completely inappropriate in the case of dense clouds. Because of this, we shall adopt here the extinction law derived for σ-Sco (Snow & York, 1975), assumed as representative of the extinction curve in a class of dense clouds. It is worthwhile noting that the σ-Sco extinction curve is a conservative choice. Indeed, the mean extinction curve towards inner region of ρ-Oph is even lower.

b) Scattering properties

γ and g can be derived, in principle, from observations of reflection nebulae and of the diffuse galactic light. However this task is more difficult to accomplish than the observation and interpretation of the interstellar extinction law. in fact only under exceptional conditions is it possible to derive the albedo and the asymmetry factor independently of one another. Furthermore, the determination of γ and g can be affected by the uncertainty of the geometrical relationship of the sources of illumination and the scatters, as well as and by the uncertainty of the illuminating spectrum. The observational results are particularly ambiguous in the far UV region.

Nor does the situation look much better when we turn to the existing models of the interstellar dust. Indeed, since the interstellar extinction curve is quite insensitive to the exact composition of the dust, it can be matched by models which exclude each other. So existing models of dust based on the fitting of the interstellar extinction curve give different values of the scattering parameters for the same spectral interval. Moreover, as stated above, the properties of dust inside the dense clouds may differ from the properties of the dust in the general interstellar medium, so the uncertainty is even greater.

It is possible, however, to derive from the observational results some indications about the scattering properties of interstellar dust. Indeed it appears that the dust is basically forward scattering and that the its albedo is smaller towards shorter wavelengths than in the visual (De Boer, 1986). Moreover, it appear possible, independent of particular grain models, to put constraints on the values allowed for the mean albedo and asymmetry factor of the dust responsible for the MIEC (Chlewicki and Greenberg, 1984). So it is possible to exclude from consideration the cases of very low values of the asymmetry factors coupled with large values of the albedo or of very large albedo coupled with completely forward scattering. Both the Mathis,Rumpl and Nordsieck (1977) and Greenberg and Chlewicki (1983) models give allowed values.

The validity of this analysis is limited to the grains as defined by the mean extinction curve. No scattering models, in our knowledge, have been worked out for the dust within the dense clouds. Some indications, however, can be obtained if the deficiency of small grains in size distribution is taken into account.

In the present computations, we used the scattering parameters measured in Orion by Mathis et al (1981). The adopted data are those of their model 5. The reason of this choice is that Orion, being a region particularly suitable for investigating the scattering properties of the dust, exhibits in the same time a flat extinction.

Finally, A_{uj}, the probability for the 629 transitions considered in the present work are from Allison and Dalgarno (1970).

3. Results

We carried out computations of photon fluxes for two different model of radial density distribution inside the cloud (gas and dust densities are assumed to have the same density distribution):

I. The cloud has a small uniform density core ($r_c = 0.1$ pc, $n(H_2) = 10^4$ cm^{-3}) plus a r^{-1} density gradient. The resulting total visual optical depth (edge to center) is 10.

II. The cloud has a small uniform density core (same parameters as in the case I) plus a r^{-2} density gradient. The total visual optical depth is 6.

In both cases the cloud radius is assumed to be equal to 1 pc.

The assumption that the interstellar UV radiation cannot penetrate inside the cloud obviously implies the existence, around our object, of an extended envelope, or that the object is located in a less dense but larger region (an example of such objects is the dark cloud B5 (Stenholm, 1985)).

The photon fluxes obtained at the center (C), in the middle (M) and at the edge (E) of the cloud are given in table 1. The resulting line spectrum is shown in fig. 1.

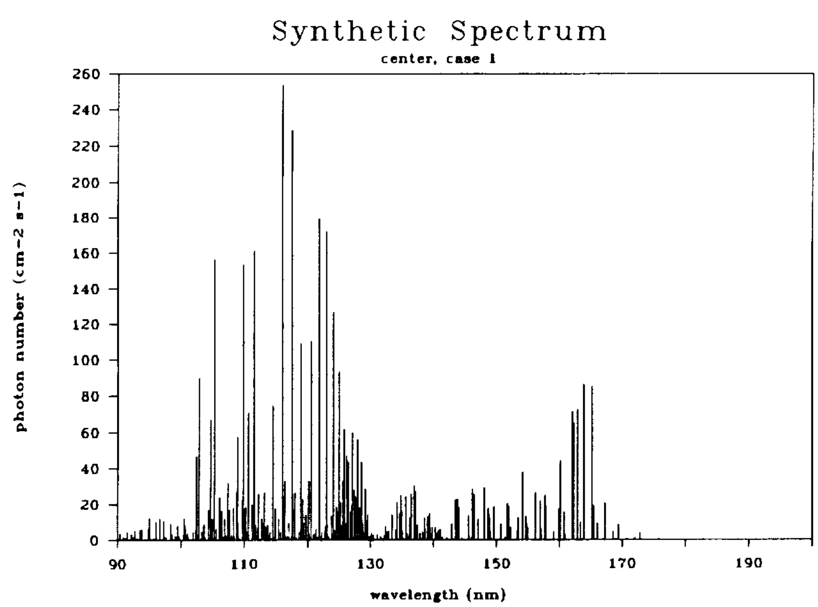

Fig.1 Synthetic emission spectrum in the Lyman and Werner bands

Our results strongly support the suggestion that the low energy cosmic rays may generate, inside dense interstellar clouds, UV radiation fields that may significantly contribute to the gas and dust evolution.

Table 1. PHOTON FLUXES (cm^{-2} s^{-1}) x 10^{-1}

	CASE I			CASE II		
	C	M	E	C	M	E
Lyman	275	220	115	470	225	80
Werner	300	240	125	515	260	90

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